# Towards a NNLO QCD+NLO EW Monte Carlo event generator for Drell-Yan production

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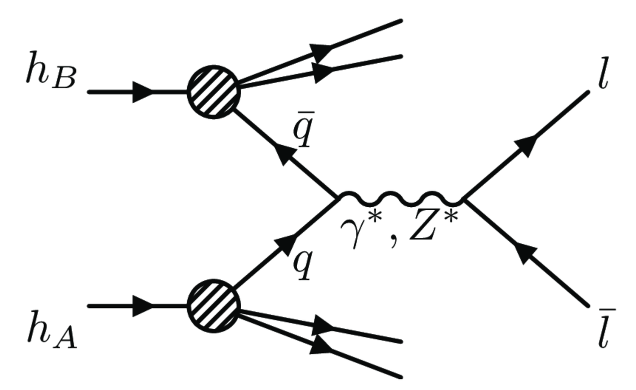
## Motivations




The neutral current Drell–Yan process constitutes one of the cornerstones of precision physics at hadron colliders

- Provides stringent tests of the Standard Model and plays a crucial role in precision measurements of EW quantities ($M_W$, $\sin\theta_W^{\text{eff}}$)
- Standard candle for constraining the PDFs and for the calibration of detector responses
- Represents a source of irreducible background in the context of new physics searches

Two fundamental aspects of EW precision measurements

- In general, the **inclusion of NLO EW effects** in the computations (and in templates) is a crucial aspect that is needed to reach the target precision.
- Lately, DY-based measurements are becoming **increasingly differential** with respect to kinematic variables such as the transverse momentum of the vector boson (which is known to be critically sensitive to QCD initial-state radiation).

In current simulation strategies

- **EW effects** are often included using tools that provide **only leading-order accuracy** in the description of the vector-boson transverse momentum.
- The **transverse momentum spectrum** is modeled using higher-order QCD calculations that **do not include EW corrections**.

The **goal** is to develop a **unified framework** capable of consistently describing **both unresolved and resolved photon emissions**, achieving **NLO QED accuracy** for observables that are inclusive with respect to the photon radiation and for events that feature hard, isolated photons.

## Merging algorithms (in QCD)

We take two generators with different multiplicity, each matched to the parton shower, that overlap over some region of the phase space

**Colour singlet** (Z) production with NLO+PS:

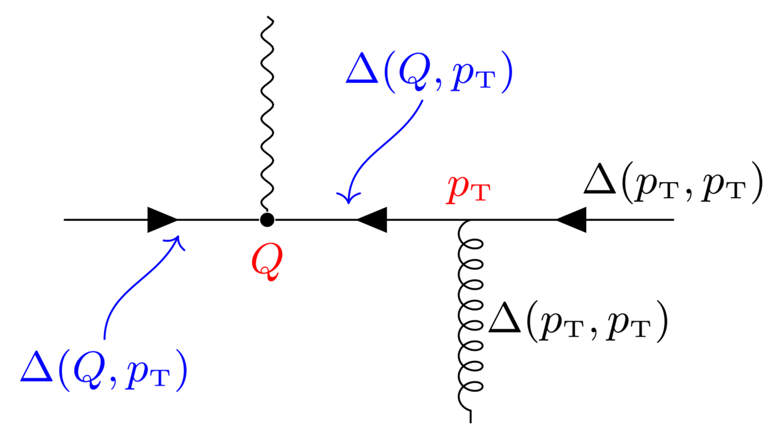
- ✓ inclusive distributions ⟶ NLO accuracy
- ✗ 1-jet distributions ⟶ LO accuracy
- ✗ 2-jet distributions ⟶ LL accuracy
- ✓ subsequent emissions ⟶ LL accuracy

**Colour singlet + one jet** (ZJ) production with NLO+PS:

- ✗ no prediction for inclusive distributions
- ✓ 1-jet distributions ⟶ NLO accuracy
- ✓ 2-jet distributions ⟶ LO accuracy
- ✓ subsequent emissions ⟶ LL accuracy

Merging algorithms are designed to build a unique framework with the best accuracy of both generators for all regions

## The MiNLO′ method




- ZJ NLO differential cross section
- include Sudakov form factors
- appropriate choice of the scales
- remove double counting

[Hamilton, Nason, Oleari, Zanderighi, arXiv:1212.4504]

$$\frac{d\sigma^{\text{MiNLO}'}}{dp_T} = \Delta^2(Q, p_T)\,\frac{\alpha_s(p_T^2)}{\alpha_s(Q^2)}\left\{\frac{d\sigma^{\text{NLO}}}{dp_T} + \frac{d\sigma^{\text{LO}}}{dp_T}\left[-2\Delta^{(1)} - \alpha_s\beta_0 \log\frac{Q^2}{p_T^2}\right]\right\}$$

Sudakov form factor:

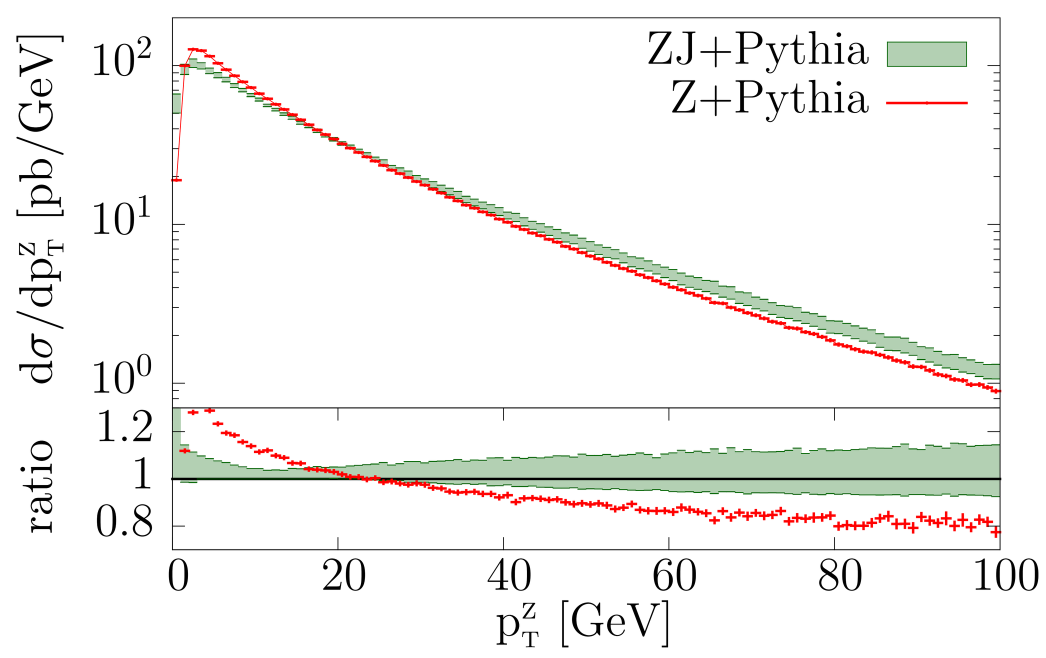
$$\Delta(Q, p_T) = e^{-S(Q,p_T)} = \exp\left\{-\int_{p_T^2}^{Q^2}\frac{dq^2}{q^2}\left[A(\alpha_s(q^2))\log\frac{Q^2}{q^2} + B(\alpha_s(q^2))\right]\right\}$$

NLO accuracy for 1-jet observables and fully inclusive ones ($p_T \to 0$ limit)

Defined for QCD ⟶ can be extended in QED via abelianization

## Numerical challenge: from QCD to QED

In QCD: $p_T^{\text{peak}} \sim 4$ GeV and $p_T^{\text{cut}} \sim \Lambda_{\text{QCD}}$



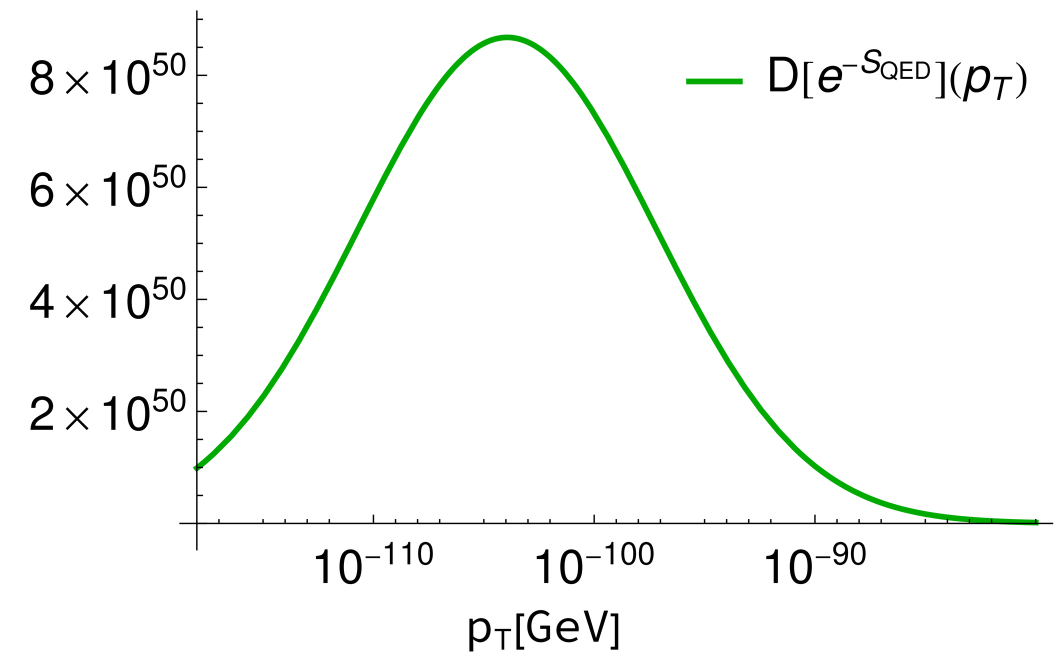

[Hamilton, Nason, Oleari, Zanderighi, arXiv:1212.4504]

- The MiNLO′ differential cross section is finite in the $p_T \to 0$ limit
- A **cutoff** $p_T^{\text{cut}}$ is still needed because the individual terms of the computation are separately divergent

In **QCD**: the MiNLO′ differential cross section (green band) has a **peak in the GeV region** and we have a natural cutoff given by the hadronization scale

In **QED**: a rough estimate (only LO effects) reveals that the position of the peak is deep in a **numerically inaccessible** region. Thus setting the cutoff to any reasonable value (e.g. $p_T^{\text{cut}} \sim 1$ GeV) would result in a large portion of the total cross section being neglected

In QED: $p_T^{\text{peak}} \sim 10^{-100} \longrightarrow p_T^{\text{cut}} = ?$




## Modifications to the method

Divide the MiNLO′ cross section into two regions, above and below a technical cutoff $p_T^c$

$$\frac{d\sigma}{d\Phi_z dp_T} = \frac{d\sigma_>}{d\Phi_z dp_T} + \frac{d\sigma_<}{d\Phi_z dp_T}$$

- In the region above $p_T^c$, the original MiNLO′ method, abelianized, is applied
- The differential cross section in the region below $p_T^c$ can instead be rewritten as

$$\frac{d\sigma_<}{d\Phi_z dp_T} = \underbrace{\frac{d}{dp_T}\left[e^{-S(Q,p_T)}\mathcal{L}(p_T)\right]}_{\text{singular for } p_T\to 0} + \underbrace{R_f(p_T)}_{\text{regular}}$$

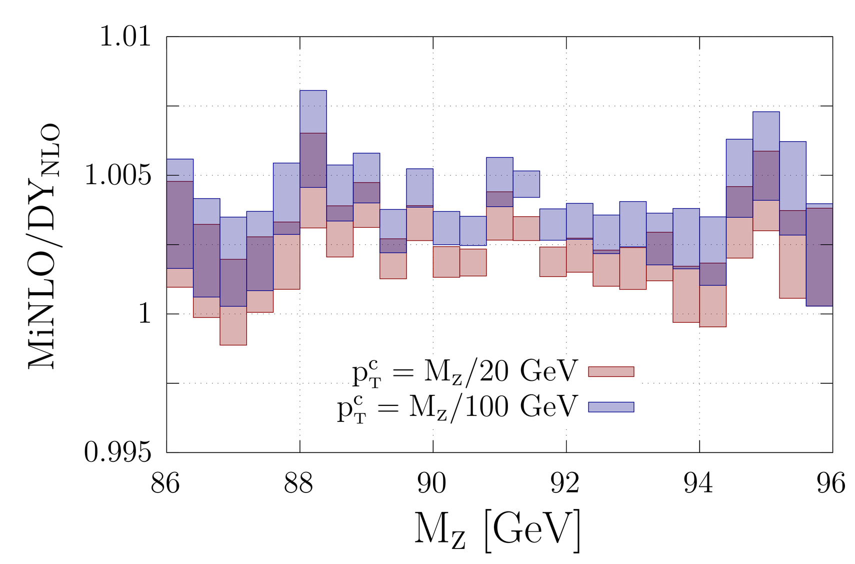
where $\mathcal{L}(p_T)$ is the luminosity. Assuming that the regular term can be neglected for $p_T < p_T^c$, the differential cross section in this region can be expressed as an exact differential in $p_T$. We can then integrate over the Z boson transverse momentum and obtain

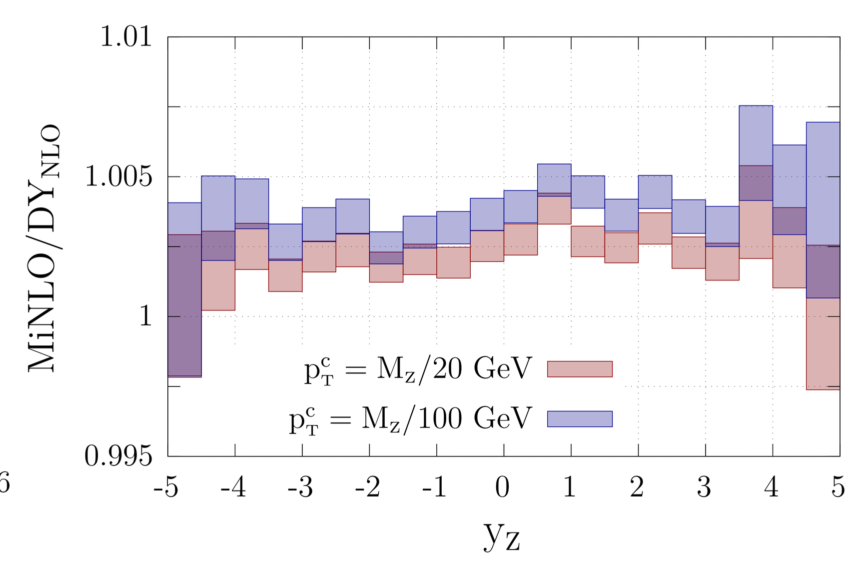
$$\frac{d\sigma_<}{d\Phi_z} = \exp\left[-S(Q, p_T^c)\right]\left\{\mathcal{L}^{(0)}(p_T^c) + \frac{\alpha(p_T^c)}{2\pi}\mathcal{L}^{(1)}(p_T^c)\right\}$$

where $\mathcal{L}^{(0)}$ and $\mathcal{L}^{(1)}$ are the first two terms, evaluated at $p_T = p_T^c$, of the expansion in powers of $\alpha$ of $\mathcal{L}(p_T)$.

## Results

This work is to be understood as a proof of concept for the abelianization of the method. For this reason QCD is turned off and all results only contain QED contributions (rescaled by a factor of 5 to enhance the corrections).




| $M_Z/p_T^c$ | $\sigma_>$ | $\sigma_<$ | $\sigma_> + \sigma_<$ | $\delta^{\text{MiNLO}'}_{\text{DY NLO}}$ |
|---|---|---|---|---|
| 10 | 38.27(2) | 698.46(4) | 736.73(4) | 0.0019(1) |
| 20 | 59.30(3) | 677.82(3) | 737.13(5) | 0.0024(1) |
| 50 | 93.13(4) | 644.52(3) | 737.66(5) | 0.0031(1) |
| 100 | 122.29(6) | 615.77(3) | 738.07(6) | 0.0037(1) |
| 200 | 153.58(8) | 584.86(3) | 738.45(8) | 0.0042(2) |

$\sigma_{\text{DY}}^{\text{NLO}} = 735.346 \pm 0.007$ pb $\quad \sigma_{\text{DY}}^{\text{LO}} = 722.817 \pm 0.004$ pb

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